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Increasing sensitivity of alpine grasslands to climate variability along an elevational gradient on the Qinghai-Tibet Plateau

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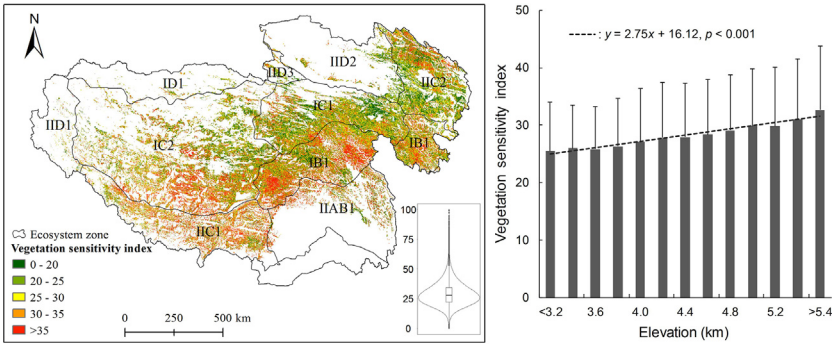
HIGHLIGHTS

- A vegetation sensitivity index-approach was modified for the Qinghai-Tibet Plateau.
- The sensitivity of alpine grasslands to climate variability was mapped.
- The climate factors driving alpine grassland dynamics are spatially heterogeneous.
- Alpine grasslands at higher elevations are more sensitive to climate variability overall.

GRAPHICAL ABSTRACT



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ABSTRACT

Monitoring and mapping the sensitivity of grassland ecosystems to climate change is crucial for developing sustainable local grassland management strategies. The sensitivity of alpine grasslands to climate change is considered to be high on the Qinghai–Tibet Plateau (QTP), yet little is known about its spatial pattern, and particularly the variations between different elevations. Here, based on the Normalized Difference Vegetation Index (NDVI) and three climate variables (air temperature, precipitation, and solar radiation), we modified a vegetation sensitivity index-approach to capture the relative sensitivity of alpine grassland productivity to climate variability on the QTP during 2000–2016. The results show that alpine grasslands on the southern QTP are more sensitive to climate variability overall, and that the climate factors driving alpine grassland dynamics are spatially heterogeneous. Alpine grasslands on the southern QTP are more sensitive to temperature variability, those on the northeastern QTP display strong responses to precipitation variability, and those on the central QTP are primarily influenced by a combination of radiation and temperature variability. The sensitivity of alpine grasslands to climate variability increases significantly along an elevational gradient, especially to temperature variability. This study underscores that alpine grasslands at higher elevations on the QTP are more sensitive to climate variability than those at lower elevations at the regional scale.

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1. Introduction

Grasslands cover 30–40% of the Earth's terrestrial surface and sustain the livelihoods of nearly 800 million people globally while also playing a significant role in global water, energy, and carbon cycling (Scurlock and Hall, 1998). There is increasing evidence that grassland vegetation is substantially affected by global climate change (Craine et al., 2012; Fay et al., 2008), especially by climate extremes (De Boeck et al., 2018; Hoover et al., 2014). In turn, changes in grassland vegetation can trigger climate feedbacks via a number of bio-physical processes, such as alterations in the energy exchange between the land and atmosphere (Shen et al., 2015b; Zeng et al., 2017). Therefore, a comprehensive understanding of the susceptibility of grassland vegetation dynamics to current climate variability is crucial for projecting future grassland dynamics and developing sustainable grassland management strategies.

The sensitivity of grassland vegetation to changing climate is complex and often varies dramatically between regions. For example, studies based on observations or experiments have shown that grasslands in semi-arid and arid areas are generally sensitive to variations in precipitation (Heisler-White et al., 2009; Knapp et al., 2015). In contrast, those in the cold regions, including at high latitudes and altitudes, are susceptible to a combination of climate warming and summer drought (Cremonese et al., 2017; De Boeck et al., 2016; Grabherr et al., 1994; Liu et al., 2018). However, previous assessments of vegetation ecosystem sensitivity at regional and global scales have primarily focused on investigating the dynamics of vegetation productivity in response to changes in the mean climate state, rather than climate variability (Huete, 2016; Rudgers et al., 2018). This limitation may hinder completely characterizing the effect of changing climate on vegetation productivity. A recent study extended such sensitivity assessments by developing a vegetation sensitivity index (VSI) that explores the linkage between variability in vegetation productivity and three climate variables (air temperature, water availability, and solar radiation) on monthly timescales (Seddon et al., 2016). The authors found that the grasslands of central Asia, North and South America are three of the ecologically sensitive regions with amplified responses to climate variability, especially water availability (Seddon et al., 2016). Nevertheless, some areas were not considered in this global assessment, such as the world's largest alpine ecosystem: the alpine grasslands of the Qinghai-Tibet Plateau (QTP) in central Asia.

The QTP, referred to as the “the world's roof” and “third pole”, primarily comprises alpine grasslands. This unique alpine grassland ecosystem has survived under extreme low temperature (Zhong et al., 2010). Annual mean temperature across most of the QTP is <0 °C, which results in high temperature-sensitive biological and chemical processes (Ding et al., 2013; Shen et al., 2016a). A range of evidence has shown that temperature has risen by 0.3–0.4 °C per decade and at about twice the global average over the past five decades (Chen et al., 2015), which has resulted in a longer thermal growing season (Dong et al., 2012; Zhao and Wu, 2016). Concurrently, annual precipitation remains <500 mm in most areas (Piao et al., 2006) but has slightly increased, and sunshine duration has slightly declined (Kuang and Jiao, 2016). Notably, the trends in all of these climate factors are spatially heterogeneous and have resulted in diverging influences on alpine grassland biodiversity, phenology and productivity (Cong et al., 2017; L. Li et al., 2018; Ma et al., 2017; Niu et al., 2019; Shen et al., 2016b), as well as distinctive changes to ecosystem services and water resources of the QTP and surrounding regions (Hopping et al., 2018; Ouyang et al., 2016; Yao et al., 2019). Previous studies have indicated that the alpine grassland of the QTP is one of the most sensitive ecosystems to global climate change, but without quantitative analyses (Sun et al., 2012). The sensitivity to climate variability for different spatial regions within this globally important ecosystem remains unclear.

Areas at higher elevations on the QTP have experienced more rapid warming compared to the lowlands since the 1960s (Liu and Chen, 2000; Yao et al., 2019) and this phenomenon is projected to strengthen by the end of the twenty-first century (Palazzi et al., 2017). Evidence is mounting that, on the QTP, elevation profoundly modulates variations in alpine grassland phenology (Li et al., 2017; Shen et al., 2014; Wang et al., 2014), as well as grassland productivity and its response to climate warming (An et al., 2018; Huang et al., 2018; Niu et al., 2019; Wang et al., 2007). For instance, An et al. (2018) found that vertical shifts in alpine vegetation greenness isolines on this plateau did not always match these of air temperature during 2000–2016. The authors linked this observation to the elevational gradient in vegetation greenness and to the lagged response of vegetation growth to warming. Given that temperature is one of the major determinants of alpine grassland growth (Grabherr et al., 1994; Körner, 2003), and that small absolute temperature increase might induce relatively greater change in the plant thermal budget in cold regions (Prevéy et al., 2017), the ecological consequences of elevation-dependent warming for plant growth is expected to be more pronounced at high elevations (Gottfried et al., 2012; D. Li et al., 2018; Pepin et al., 2015; Suonan et al., 2019). However, the relationship between sensitivity of alpine grassland to climate variability and elevation on the QTP are not yet fully understood (An et al., 2018; Tao et al., 2015).

The vegetation sensitivity index is a useful metric to quantitatively assess the sensitivity of different global ecosystems to climate variability (Huete, 2016; Willis et al., 2018). In this study, we aim to map the spatial pattern of alpine grassland sensitivity to climate variability over the QTP during 2000–2016 by tailoring the vegetation sensitivity index-approach proposed in Seddon et al. (2016). We then test the hypothesis that the sensitivity of alpine grasslands to climate variability depends on elevation, and that alpine grasslands at higher elevations are more sensitive to changing climate than those at lower elevations.

2. Materials and methods

2.1. Study area

As the largest and highest geographical unit in the world, with an average elevation higher than 4000 m above sea level (Fig. 1), the QTP is mostly characterized by low temperature; with annual mean temperature ranging from −15 °C to 10 °C (You et al., 2013). This sustained low temperature makes the QTP the largest expanse of high-elevation permafrost in the world. Precipitation on the QTP is generally concentrated between June and September; the amount ranges from >1000 mm to <50 mm and conforms to a southeast–northwest gradient. In addition, the QTP is characterized by strong solar radiation, ranging between 6000 and 9000 MJ m^{-2} yr^{-1}. These uniquely harsh climate features of the QTP have led to the development of a range of unique ecosystems (Fig. 1) (Zheng, 1996). Similar to most of the Arctic Region, the QTP, especially the northwestern part, experiences low-intensity human disturbance (S. Li et al., 2018), which provides an ideal location for investigating alpine grassland responses to changing climate over a large region (Piao et al., 2006).

2.2. Data source and pre-processing

The NDVI, based on the reflectance in the red and near-infrared bands, has been validated as a useful surrogate for vegetation productivity and has been widely employed to infer the response of vegetation dynamics (Huete et al., 2002; Myneni et al., 1997). MODIS-Terra NDVI (MOD13A2) from the Collection 6 datasets for 2000–2016 was obtained from the National Aeronautics and Space Administration (NASA, https://ladsweb.modaps.eosdis.nasa.gov/) (Didan et al., 2015). The spatial resolution of this dataset is 1 km × 1 km and the temporal resolution is 16 days. This dataset has been calibrated for atmospheric, scan angle, and varying solar zenith angle effects at the time of measurement (Didan et al., 2015). Importantly, this dataset has also been updated using an improved calibration approach to address the impact of the sensor degradation problem (Lyapustin et al., 2014). To further

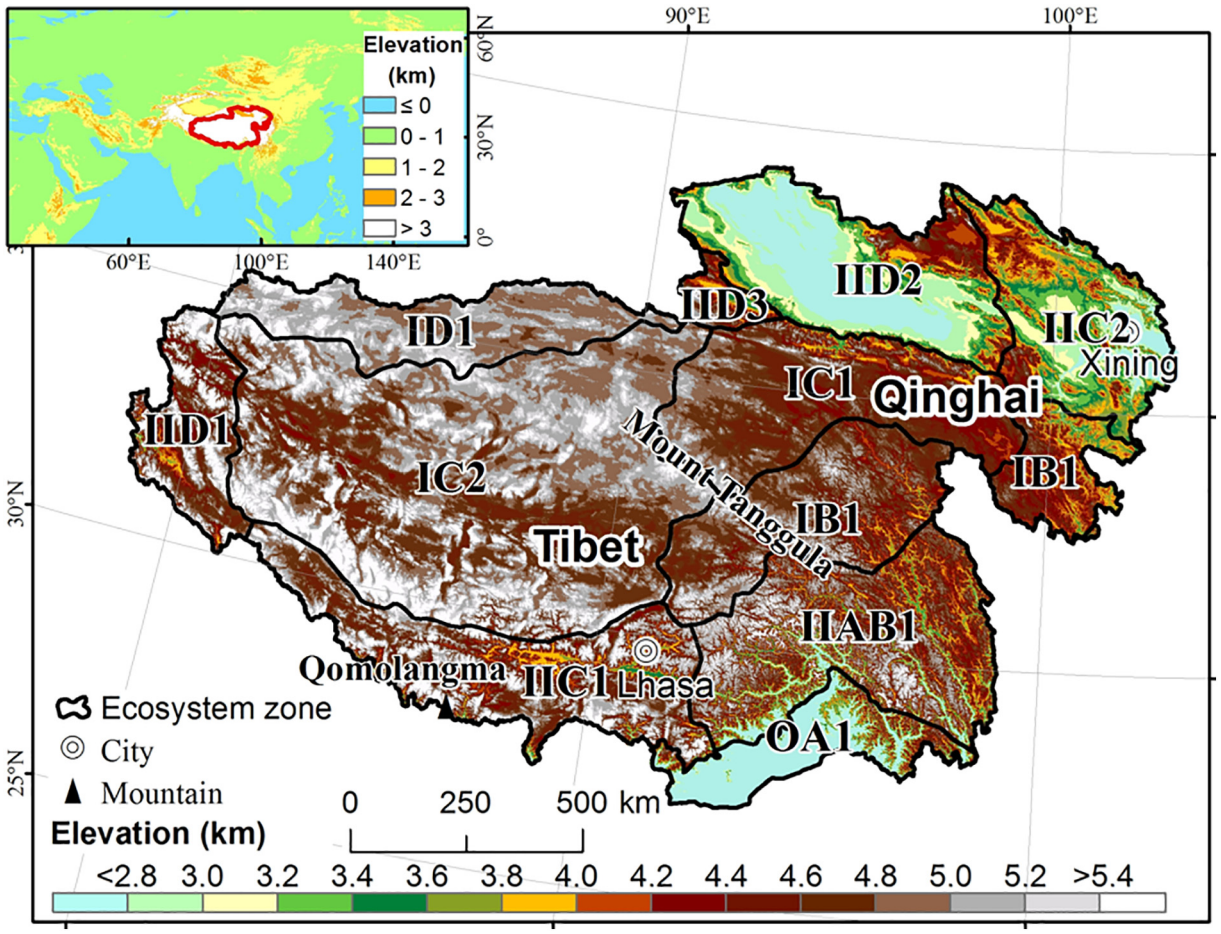

Fig. 1. Geomorphological features and ecosystem zones on the Qinghai-Tibet Plateau (QTP). Ecosystem zones on the QTP include the temperate humid/sub-humid western Sichuan-eastern Tibet montane coniferous forest zone (IIAB1), sub-cold sub-humid Guoluo-Naqu mountain alpine shrub-meadow zone (IB1), temperate semi-arid eastern Qinghai-Qilian montane steppe zone (IIC2), sub-cold semi-arid southern Qinghai alpine meadow-steppe (IC1), Qiangtang alpine steppe zones (IC2), temperate semi-arid southern Tibet montane shrub-steppe zone (IIC1), temperate arid Qaidam Basin desert region (IID2), temperate arid north Kunlun desert zone (IID3), sub-cold arid Kunlun mountain and plateau alpine steppe zone (ID1), and temperate arid Ngali montane desert zone (IID1).

eliminate contamination caused by clouds, snow, and ice cover, we applied an adaptive Savitzky–Golay approach to smooth the annual NDVI cycle and reconstruct a time series using the TIMESAT software package in the MATLAB environment (Jönsson and Eklundh, 2004). In addition, to eliminate the potential impact of noisy data at sparsely vegetated areas, pixels with mean growing-season NDVI values < 0.10 were masked out in this analysis (Shen et al., 2015b).

Consistent with the period of MODIS-Terra NDVI data, gridded reanalysis meteorological datasets, including mean daily air temperature, precipitation, and solar radiation, were obtained from the China Meteorological Forcing Dataset (CMFD, http://dam.itpcas.ac.cn/) (Chen et al., 2011; Tang et al., 2011). Air temperature data at 2 m height was a combination of records from China's 740 meteorological stations and Princeton forcing data (Sheffield et al., 2006). Precipitation data was produced by merging records from meteorological stations and TRMM precipitation data (3B42). Solar radiation data was generated by assimilating records from meteorological stations, GEWEX-SRB, and the GLDAS dataset. These gridded reanalysis climate datasets have relatively high accuracy and have been applied to capture the response of vegetation ecosystems to climate change (L. Li et al., 2018; Shen et al., 2016a). Climate datasets were resampled to a spatial resolution of 1 km using the bilinear interpolation method (An et al., 2018). We acknowledge that, while this interpolation matches the grid of MODIS-Terra NDVI and climate data, it was not possible to eliminate uncertainties in spatial variation because of the coarse spatial resolution (0.1° × 0.1°) of the climate data.

To evaluate the relationship between the sensitivity of alpine grasslands to climate variability and elevation over the QTP, topography data were obtained from the United States Geological Survey global digital elevation model with a spatial resolution of approximately 1 km (https://lta.cr.usgs.gov/GTOPO30). The spatial distribution of alpine grassland was extracted from vegetation cover data provided by the Institute of Botany, Chinese Academy of Sciences (Zhang et al., 2007).

2.3. Identifying the sensitivity of alpine grassland to climate variability

The VSI is a novel and empirical metric developed by Seddon et al. (2016) that can quantify the sensitivity of different vegetation areas to climate variability (Huete, 2016; Willis et al., 2018). The VSI in each pixel is quantified based on the monthly mean–variance relationship between the Enhanced Vegetation Index (EVI) and three climate variables (air temperature, water availability and cloud cover) and their relative weights (Seddon et al., 2016). However, the length of growing season in alpine grasslands has been underestimated due to the low air temperature derived from satellite images and the extensive permafrost distributed at high elevations on the QTP. This might be the reason why Seddon et al. (2016) did not include alpine grasslands on the QTP in the assessment of global ecosystems' sensitivity to climate variability.

In this study, we tailored the empirical methodology to identify alpine grassland areas sensitive to climate variability on the QTP. We initially selected 16-day MODIS-Terra NDVI as a proxy for vegetation productivity instead of the monthly EVI, because NDVI generally

performs better for low-density canopies and grasslands (Huete et al., 2002; Ji and Peters, 2007). We then utilized the NDVI time series to extract spring and autumn vegetation phenology using the dynamic threshold method in the TIMESAT program. Details of the parameters used for phenology extraction are described in Zu et al. (2018). Mean spring and autumn phenology data for the QTP alpine grasslands at the start and end of the growing season, respectively, were used in this study instead of monthly temperatures > 0 °C, which were then matched with the corresponding date in the 16-day NDVI data (see Fig. S1 in Supplementary materials). It is worth noting that this study selected the 16-day time interval as the timescale to investigate the sensitivity of alpine grassland productivity to climate variability, rather than the monthly timescale in Seddon et al. (2016), because the growing season on the QTP is very short (Fig. S1). Furthermore, for three major climatic variables, we employed air temperature, precipitation, and solar radiation data from the CMFD, instead of those solely derived from MODIS as in Seddon et al. (2016). Finally, to analyze the potential influence of memory effects on alpine grassland vegetation growth, according to the findings of Seddon et al. (2016) and D. Li et al. (2018), two 16-day lagged NDVI anomalies were chosen as the fourth $(t-2)$ variable. In this study, the sensitivity of alpine grassland productivity to climate variability on the QTP was primarily calculated using AR1 multiple linear regression approach in each pixel, as follows:

$$NDVI_t[i] = \alpha Tem_t[i] + \beta Pre_t[i] + \gamma Rad_t[i] + \lambda NDVI_{t-2}[i] + \varepsilon$$

where, $NDVI_t$ and $NDVI_{t-2}$ denote the standardized 16-day NDVI anomaly series at time t and $t-2$ of pixel i, respectively. Tem_t, Pre_t, and Rad_t refer to the standardized air temperature, precipitation, and solar radiation anomaly series at time t of pixel i, respectively; ε denotes the residual error. $\alpha(i)$, $\beta(i)$, $\gamma(i)$, and $\lambda(i)$ are the coefficients for temperature, precipitation, solar radiation, and $NDVI_{t-2}$ anomalies of pixel i, respectively. $\alpha(i)$ refers to the temperature sensitivity index denoting the magnitude of immediate response of vegetation growth to the contemporary variation in temperature. Similarly, $\beta(i)$ and $\gamma(i)$ denote the water sensitivity index and radiation sensitivity index, respectively. $\lambda(i)$ denotes the importance of the two 16-day lagged responses in alpine grassland productivity, which reveals the memory effects in determining alpine grassland productivity.

In order to eliminate the effect of co-linearity between there climate variables, the principal components regression (PCR) was also applied within each pixel to quantify the relative importance of each variable driving variations in the 16-day NDVI (Seddon et al., 2016). The variance of both NDVI and each climatic variable was calculated, and the log10-transformed ratios of NDVI variability and each of the climate variables were then estimated. The ratios were weighted according to the importance of each climate variable using the PCR. Finally, the VSI was calculated by summing sensitivity scores for each variable. To ensure comparability between coefficients, all of the time series were detrended and standardized. In this study, VSI, $\alpha(i)$, $\beta(i)$, $\gamma(i)$, and $\lambda(i)$ were rescaled 0 to 100 using the minimum and maximum values of individual variables. The VSI has no units and therefore provides relative information, wherein a high VSI value is associated with a high response rate of vegetation productivity to climate variability. The detailed algorithm for calculating VSI and the R script can be found in Seddon et al. (2016).

3. Results

3.1. Spatial patterns of alpine grassland sensitivity to climate variability

The values of VSI on the southern QTP tended to be higher overall than those on the north over the study period (Fig. 2a), indicating that alpine grasslands across most of the southern QTP were characterized by higher ecological sensitivity to climate variability. Meanwhile, VSI values varied between ecosystem zones (Fig. 2b). Specifically, ecologically sensitive regions were characterized by enhanced responses to climate variability, including zones IIC1, IIAB1, and IB1 and the southern part of zone IC2. Contrasting low VSI values in zones IIC2, IC1, IID2, and the northern part of zone IC2 indicate alpine grasslands with low sensitivity to climate variability. We also identified a small number of high VSI values sporadically distributed on the northern QTP, such as the northern part of zone IIC2.

3.2. Spatial patterns of climate factors driving alpine grassland dynamics

The relative contribution of three climate variables (temperature, precipitation, and radiation) to vegetation sensitivity displayed clear spatially heterogeneity across the region (Fig. 3). Alpine grasslands on the southeastern QTP were sensitive to temperature variability, while alpine grasslands on the northeastern and mid-western parts of the plateau were primarily influenced by a combination of precipitation and radiation. In comparison, alpine grasslands on the central and western QTP were more sensitive to a combination of radiation and temperature.

Notably, the central region of zones IIC2 and IID2 and the eastern part of zone IC1were characterized by low-value climate coefficient weights, while high values were calculated for the southwestern QTP and eastern part of zone IB1. In contrast, these areas exhibited memory effects with respectively high and low values (the coefficient for $NDVI_{t-2}$ anomalies in AR1 model) (Fig. 4) and respectively low and high VSI values (Fig. 2). These results indicate that alpine grassland areas on the QTP with low climate weights or low VSI values displayed strong memory effects.

3.3. Elevation dependence of alpine grassland sensitivity to climate variability

To quantify the influence of elevational gradient on alpine grassland sensitivity to climate variability, we calculated average VSI values at 200-m elevation intervals. The results show that VSI values increased significantly along an elevational gradient on the study period ($p < 0.001$, Figs. 5 and S2), suggesting that alpine grassland at higher elevations are more sensitive to climate variability than those at lower elevations on the QTP.

3.4. Elevational gradients in climate sensitivity indices of alpine grassland

Mean climate sensitivity indices for temperature, precipitation, and radiation and the values of memory effects were also calculated at 200-m elevation intervals. The values of temperature sensitivity index substantially increased along an elevational gradient over the study period ($p < 0.001$, Figs. 6 and S2), which is consistent with the elevation dependence of VSI values (Fig. 5). However, both the water sensitivity index and radiation sensitivity index increased along an elevational gradient with clear fluctuations and displayed weaker relationships with elevation than the temperature sensitivity index. In contrast, the values of memory effects substantially declined along an elevational gradient ($p < 0.001$, Figs. 7 and S2), indicating that memory effects play a more significant role in driving alpine grassland productivity at lower elevation.

4. Discussion

4.1. Spatial heterogeneity in the climate sensitivity of alpine grassland

The degree of spatial heterogeneity we identified in the three climate factors driving alpine grassland vegetation dynamics (temperature, precipitation, and radiation) is partially consistent with previous studies. Earlier studies investigating vegetation dynamics in response to changes in the mean climate state have also noted, for example, that alpine vegetation on the southeastern QTP shows strong responses to temperature (Huang et al., 2016; Xu et al., 2008), while it is limited by precipitation

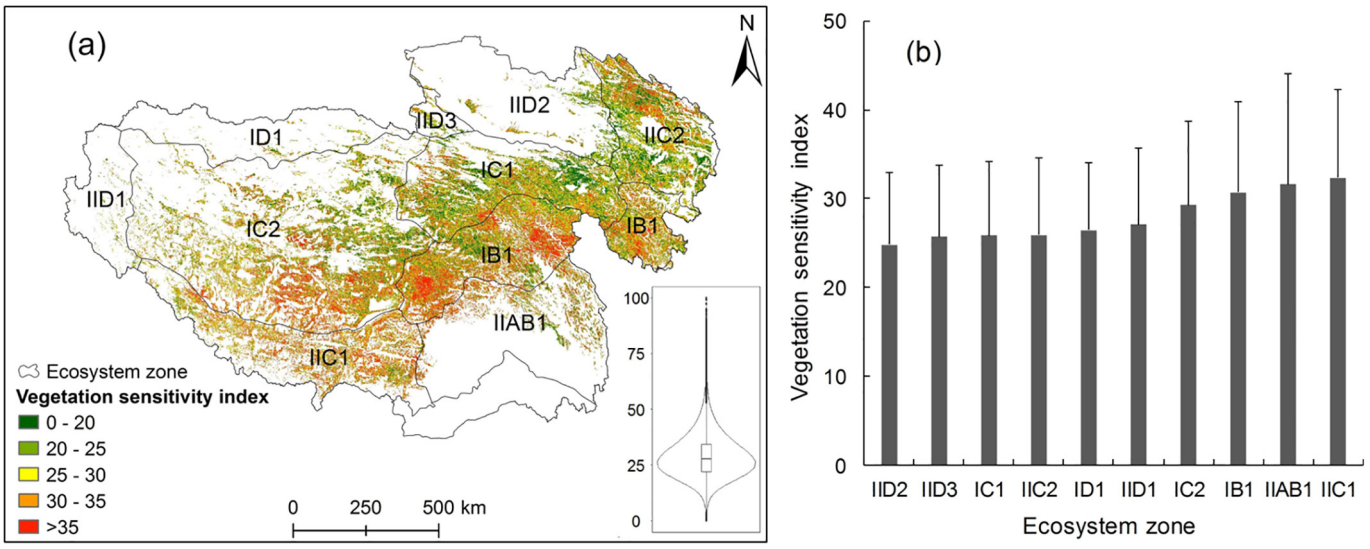

Fig. 2. Spatial patterns of vegetation sensitivity index (VSI) in alpine grasslands of the Qinghai-Tibet Plateau (QTP) during 2000–2016 (a) and mean VSI of pixels for each ecosystem zone (b). This index is relative and values range between 0 and 100. The inset panel of violin plot in (a) shows the frequency distribution of pixel VSI values, and the error bars in (b) indicate standard deviations of pixel VSI values in each ecosystem zone. Pixels with growing season NDVI < 0.10 were masked out, and about 6.25×10^5 pixels were considered.

on the northeastern part of the plateau (L. Li et al., 2018; Liu et al., 2017). One potential explanation of this phenomenon is that vegetation activity on the QTP is more sensitive to temperature variations in wetter and colder regions and more sensitive to precipitation variations in drier regions (Shen et al., 2015a; Xu et al., 2008). Furthermore, Piao et al. (2006) noted that alpine vegetation productivity at a regional scale across the QTP might be driven by radiation and temperature, while our results reveal strong responses in alpine grasslands to radiation variability primarily in the central and northwestern QTP (Fig. 3). Additionally, compared with another global-scale assessment indicating that alpine vegetation productivity on the QTP is limited by a combination of temperature and precipitation (Nemani et al., 2003), our results showed more spatial heterogeneity in the main climatic drivers, likely due to the regional scale of this study and application of the more advanced modified model of Seddon et al. (2016).

4.2. Elevation dependence of sensitivity of alpine grassland to climate variability

We investigated the relationship between the sensitivity of alpine grassland ecosystem to climate variability and elevation on the QTP, extending sensitivity assessments of terrestrial ecosystems in the vertical dimension. We found that both the mean VSI value and temperature sensitivity index increase significantly along an elevational gradient (Figs. 5 and 6), which is in agreement with global assessments for areas surrounding the QTP and other alpine region (D. Li et al., 2018)

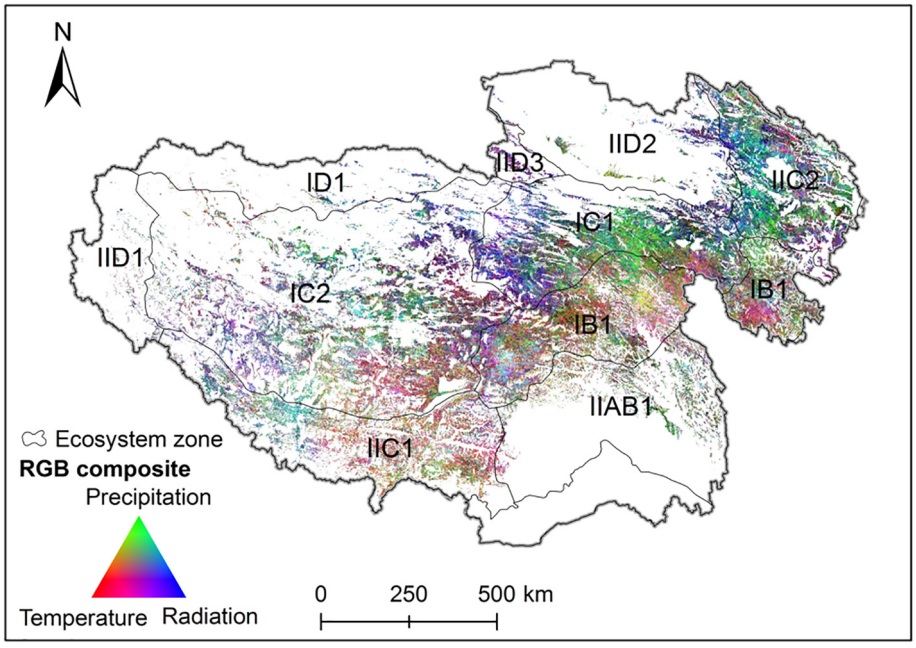

Fig. 3. RGB composite of vegetation sensitivity index (VSI) for the alpine grasslands of the Qinghai-Tibet Plateau (QTP). Contribution of three climate variables to VSI (temperature, red; precipitation, green; and radiation, blue).

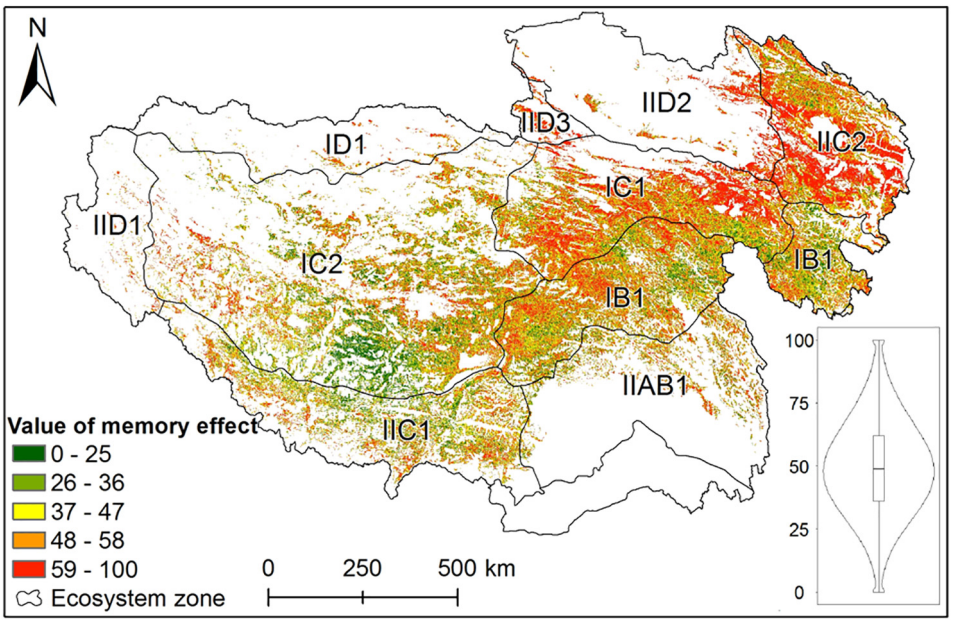

Fig. 4. Spatial variation in the memory effects of alpine grassland productivity on the Qinghai-Tibet Plateau (QTP) during 2000–2016. The inset violin plot shows the frequency distribution of the pixel values.

and the eastern QTP (You et al., 2018). Elevation influences grassland vegetation primarily by affecting temperature, water availability and their combinations, which subsequently affect ecosystem properties (Tao et al., 2015).

Air temperature drops along elevational gradients, but small increase in air temperature might represent relative larger increase in thermal balance in colder regions (Prevéy et al., 2017), which partly leads to enhanced temperature sensitivity of biological and chemical processes at high elevations (Chen et al., 2013; Ernakovich et al., 2014). Meanwhile, elevation-dependent warming on the QTP over recent decades has been confirmed (Liu and Chen, 2000; Yao et al., 2019), which has reduced low-temperature limitations on alpine vegetation growth in high elevations (Keenan and Riley, 2018; Piao et al., 2011; Shen et al., 2016a). On the one hand, accelerated warming at high elevations could directly stimulate alpine vegetation productivity by alleviating the restriction on vegetation growth rate. On the other hand, climate warming supplies more nutrients for alpine vegetation growth through enhancing the decomposition of vegetation litter and soil organic matter and N mineralization. Notably, previous studies have found a significant correlation between variations in alpine grassland vegetation and temperature change at higher elevations in Qinghai Province and the mountains of southwest China (Tao et al., 2018, 2015). Additionally, Suonan et al. (2019) found that the phenological sensitivity of leaf-out day on the QTP is about seven times larger than the global average,

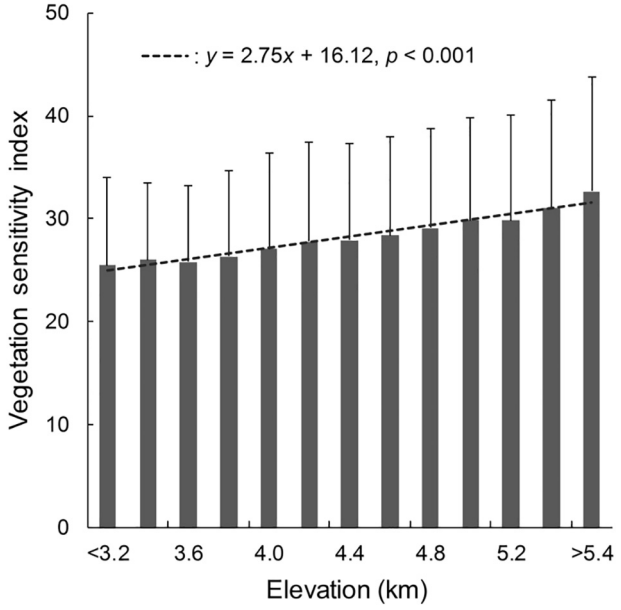

Fig. 5. Elevation dependence of the vegetation sensitivity index (VSI) for alpine grasslands on the Qinghai-Tibet Plateau (QTP). The error bars indicate the standard deviation of the pixels in each elevation bin.

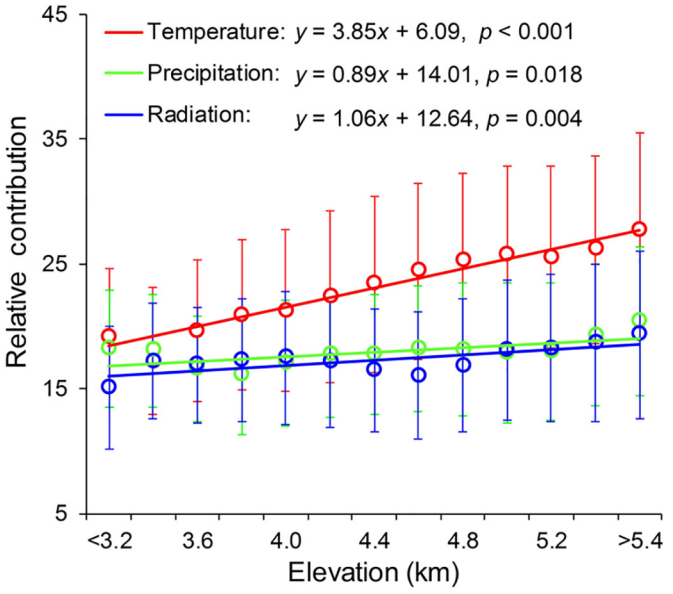

Fig. 6. Elevational gradients in mean climate sensitivity indices for alpine grasslands on the Qinghai-Tibet Plateau (QTP). The error bars denote the standard deviation of pixels within each elevation bin.

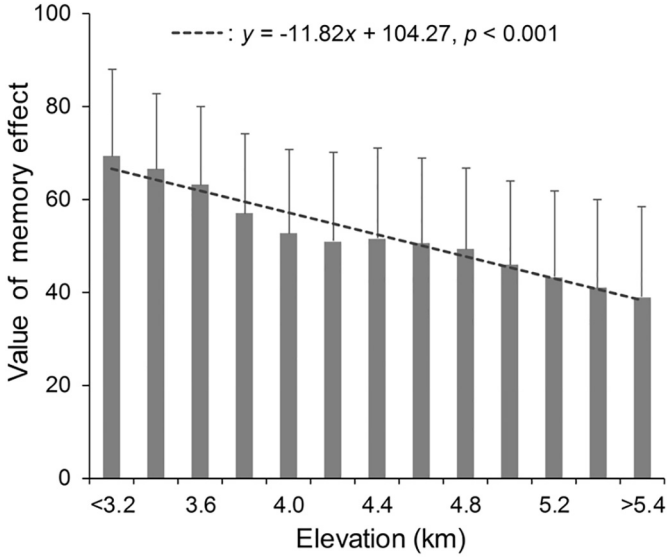

Fig. 7. Elevation dependence of memory effects of alpine grassland productivity on the Qinghai-Tibet Plateau (QTP). The error bars denote the standard deviation of pixels within each elevation bin.

and Prevéy et al. (2017) highlighted the greater temperature sensitivity of plant phenology distributed in colder areas across northern latitudes. Thus, the greater sensitivity of alpine grasslands to climate variability at higher elevations is also associated with the short growing season and its variations (Lamprecht et al., 2018). It is important to note that climate warming also results in earlier snow-melt and degradation of permafrost, enhances the peak season water stress, and therefore constrains alpine vegetation growth to some extent (An et al., 2018; Keenan and Riley, 2018; Yang et al., 2018).

Elevation-dependent warming on the QTP is projected to strengthen by the end of the twenty-first century (Palazzi et al., 2017), and our results showed that temperature sensitivity index increases along an elevational gradient on this plateau during 2000–2016. These phenomena suggest not only an expected decline in low-temperature limitation on alpine vegetation growth over the QTP under future warming scenarios (Keenan and Riley, 2018), but also more pronounced ecological consequences for alpine grassland at high elevations.

4.3. Limitations and future work

Although the method proposed by Seddon et al. (2016) was regionalized for evaluating the QTP, an ecologically high-value area not considered in recent global assessments, a number of uncertainties remain in this study. For example, precipitation during the growing season might be an imperfect proxy for water availability on the QTP; therefore, the sensitivity of alpine grassland productivity to precipitation variability might be underestimated. Precipitation during the growing season directly affects grassland vegetation growth, while at other times, this variable exerts a potentially lagged effect via soil water (Desai et al., 2016; Robertson et al., 2009). Moreover, the lagged responses of vegetation growth to precipitation input via soil water are related to recharge processes, particularly in water-limited regions and those characterized by permafrost and snow cover on the QTP (Qiu et al., 2019; Ran et al., 2018). In the southwestern QTP, our results showed that alpine grassland productivity is more sensitive to contemporary temperature conditions than to precipitation and radiation (Fig. 2). However, previous studies have shown a systematic reduction in the growing-season NDVI that might also be related to pre-monsoonal droughts (Shen et al., 2015b, 2014). Thus, future studies should address the potential lag effects of climate variability on vegetation growth for different periods.

In addition, human activities (D. Li et al., 2018; Peters et al., 2019) and underlying physical and biological processes that might drive diverse vulnerability among species (Huete, 2016; Lee et al., 2018) and successional states (Kröel-Dulay et al., 2015) should also be taken into account in future studies. Since 2004, the Chinese government has, for example, launched a number of ecological restoration projects (e.g. the Grazing Withdrawal Program) with the goal of recovering degraded alpine grassland on the QTP. Although these projects have improved the overall health of alpine grasslands in this region (Zhang et al., 2014), degraded or recovering ecosystems may be more sensitive to climate variability (Kröel-Dulay et al., 2015).

5. Conclusions

This study provides a comprehensive quantification of the sensitivity of alpine grasslands to recent climate variability on the QTP and extends global sensitivity assessments of terrestrial ecosystems in the vertical dimension. For the period of 2000–2016, we found that alpine grasslands characterized by higher climatic sensitivity were primarily located on the southern QTP. However, the relative contributions of major climate factors, i.e., temperature, precipitation, and radiation, to alpine grassland sensitivity were spatially heterogeneous. Mean values of VSI and the temperature sensitivity index increased significantly along an elevational gradient on the QTP, indicating that alpine grasslands at higher elevations were more sensitive to climate variability overall, especially to rapid temperature warming. These results will help us assess the ecological consequences of global climate variability, particularly at high elevations, and develop optimal adaptive strategies for grassland management to protect this vulnerable ecosystem.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2019.04.399.

References

An, S., Zhu, X., Shen, M., Wang, Y., Cao, R., Chen, X., Tang, Y., 2018. Mismatch in elevational shifts between satellite observed vegetation greenness and temperature isolines during 2000–2016 on the Tibetan Plateau. Glob. Chang. Biol. 24, 5411–5425.

Chen, Y., Yang, K., He, J., Qin, J., Shi, J., Du, J., He, Q., 2011. Improving land surface temperature modeling for dry land of China. Journal of Geophysical Research: Atmospheres 116, D20104.

Chen, H., Zhu, Q., Peng, C., Wu, N., Wang, Y., Fang, X., Wu, J., 2013. The impacts of climate change and human activities on biogeochemical cycles on the Qinghai-Tibetan Plateau. Glob. Chang. Biol. 19, 2940–2955.

Chen, D., Xu, B., Yao, T., Guo, Z., Cui, P., Chen, F., ... Zhang, T., 2015. Assessment of past, present and future environmental changes on the Tibetan Plateau. Chin. Sci. Bull. 60, 3025–3035.

Cong, N., Shen, M., Yang, W., Yang, Z., Zhang, G., Piao, S., 2017. Varying responses of vegetation activity to climate changes on the Tibetan Plateau grassland. Int. J. Biometeorol. 1–12.

Craine, J.M., Ocheltree, T.W., Nippert, J.B., Towne, E.G., Skibbe, A.M., Kembel, S.W., Fargione, J.E., 2012. Global diversity of drought tolerance and grassland climate-change resilience. Nat. Clim. Chang. 3, 63–67.

Cremonese, E., Filippa, G., Galvagno, M., Siniscalco, C., Oddi, L., Morra Di Cella, U., Migliavacca, M., 2017. Heat wave hinders green wave: the impact of climate extreme on the phenology of a mountain grassland. Agric. For. Meteorol. 247, 320–330.

De Boeck, H.J., Bassin, S., Verlinden, M., Zeiter, M., Hiltbrunner, E., 2016. Simulated heat waves affected alpine grassland only in combination with drought. New Phytol. 209, 531–541.
De Boeck, H.J., Hiltbrunner, E., Verlinden, M., Bassin, S., Zeiter, M., 2018. Legacy effects of climate extremes in alpine grassland. Front. Plant Sci. 9.
Desai, A.R., Wohlfahrt, G., Zeeman, M.J., Katata, G., Eugster, W., Montagnani, L., Schmid, H., 2016. Montane ecosystem productivity responds more to global circulation patterns than climatic trends. Environ. Res. Lett. 11, 024013.
Didan, K., Munoz, A.B., Solano, R., Huete, A., 2015. MODIS Vegetation Index User's Guide. MOD13 SeriesVegetation Index and Phenology Lab, The University of Arizona.
Ding, M., Zhang, Y., Sun, X., Liu, L., Wang, Z., Bai, W., 2013. Spatiotemporal variation in alpine grassland phenology in the Qinghai-Tibetan Plateau from 1999 to 2009. Chin. Sci. Bull. 58, 396–405.
Dong, M., Jiang, Y., Zheng, C., Zhang, D., 2012. Trends in the thermal growing season throughout the Tibetan Plateau during 1960–2009. Agric. For. Meteorol. 166–167, 201–206.
Ernakovich, J.G., Hopping, K.A., Berdanier, A.B., Simpson, R.T., Kachergis, E.J., Steltzer, H., Wallenstein, M.D., 2014. Predicted responses of arctic and alpine ecosystems to altered seasonality under climate change. Glob. Chang. Biol. 20, 3256–3269.
Fay, P.A., Kaufman, D.M., Nippert, J.B., Carlisle, J.D., Harper, C.W., 2008. Changes in grassland ecosystem function due to extreme rainfall events: implications for responses to climate change. Glob. Chang. Biol. 14, 1600–1608.
Gottfried, M., Pauli, H., Futschik, A., Akhalkatsi, M., Barančok, P., Benito Alonso, J.L., Grabherr, G., 2012. Continent-wide response of mountain vegetation to climate change. Nat. Clim. Chang. 2, 111–115.
Grabherr, G., Gottfried, M., Paull, H., 1994. Climate effects on mountain plants. Nature 369, 448.
Heisler-White, J.L., Blair, J.M., Kelly, E.F., Harmoney, K., Knapp, A.K., 2009. Contingent productivity responses to more extreme rainfall regimes across a grassland biome. Glob. Chang. Biol. 15, 2894–2904.
Hoover, D.L., Knapp, A.K., Smith, M.D., 2014. Resistance and resilience of a grassland ecosystem to climate extremes. Ecology 95, 2646–2656.
Hopping, K.A., Knapp, A.K., Dorji, T., Klein, J.A., 2018. Warming and land use change concurrently erode ecosystem services in Tibet. Glob. Chang. Biol. 24, 5534–5548.
Huang, K., Zhang, Y., Zhu, J., Liu, Y., Zu, J., Zhang, J., 2016. The influences of climate change and human activities on vegetation dynamics in the Qinghai-Tibet Plateau. Remote Sens.-Basel 8, 876.
Huang, N., He, J., Chen, L., Wang, L., 2018. No upward shift of alpine grassland distribution on the Qinghai-Tibetan Plateau despite rapid climate warming from 2000 to 2014. Sci. Total Environ. 625, 1361–1368.
Huete, A., 2016. Ecology: vegetation's responses to climate variability. Nature 531, 181–182.
Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X., Ferreira, L.G., 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. Remote Sens. Environ. 83, 195–213.
Ji, L., Peters, A.J., 2007. Performance evaluation of spectral vegetation indices using a statistical sensitivity function. Remote Sens. Environ. 106, 59–65.
Jönsson, P., Eklundh, L., 2004. TIMESAT—a program for analyzing time-series of satellite sensor data. Comput. Geosci.-Uk 30, 833–845.
Keenan, T.F., Riley, W.J., 2018. Greening of the land surface in the world's cold regions consistent with recent warming. Nat. Clim. Chang. 8, 825–828.
Knapp, A.K., Carroll, C.J.W., Denton, E.M., La Pierre, K.J., Collins, S.L., Smith, M.D., 2015. Differential sensitivity to regional-scale drought in six central US grasslands. Oecologia 177, 949–957.
Körner, C., 2003. Alpine Plant Life-Functional Plant Ecology of High Mountain Ecosystems. Springer, Heidelberg, Germany.
Kröel-Dulay, G., Ransijn, J., Schmidt, I.K., Beier, C., De Angelis, P., de Dato, G., ... Penuelas, J., 2015. Increased sensitivity to climate change in disturbed ecosystems. Nat. Commun. 6, 6682.
Kuang, X., Jiao, J.J., 2016. Review on climate change on the Tibetan Plateau during the last half century. Journal of Geophysical Research: Atmospheres 121, 3979–4007.
Lamprecht, A., Semenchuk, P.R., Steinbauer, K., Winkler, M., Pauli, H., 2018. Climate change leads to accelerated transformation of high-elevation vegetation in the central Alps. New Phytol. 220, 447–459.
Lee, C.K.F., Duncan, C., Owen, H.J.F., Pettorelli, N., 2018. A new framework to assess relative ecosystem vulnerability to climate change. Conserv. Lett. 11, e12372.
Li, L., Liu, L., Zhang, Y., Ding, M., Li, S., Chen, Q., 2017. Elevation-dependent alpine grassland phenology on the Tibetan Plateau. Geogr. Res. 36, 26–36.
Li, D., Wu, S., Liu, L., Zhang, Y., Li, S., 2018. Vulnerability of the global terrestrial ecosystems to climate change. Glob. Chang. Biol. 24, 4095–4106.
Li, L., Zhang, Y., Liu, L., Wu, J., Wang, Z., Li, S., Paudel, B., 2018. Spatiotemporal patterns of vegetation greenness change and associated climatic and anthropogenic drivers on the Tibetan Plateau during 2000–2015. Remote Sens.-Basel 10, 1525.
Li, S., Zhang, Y., Wang, Z., Li, L., 2018. Mapping human influence intensity in the Tibetan Plateau for conservation of ecological service functions. Ecosystem Services 30, 276–286.
Liu, X., Chen, B., 2000. Climatic warming in the Tibetan Plateau during recent decades. Int. J. Climatol. 20, 1729–1742.
Liu, S., Zhang, Y., Cheng, F., Hou, X., Zhao, S., 2017. Response of grassland degradation to drought at different time-scales in Qinghai Province: spatio-temporal characteristics, correlation, and implications. Remote Sens.-Basel 9, 1329.
Liu, H., Mi, Z., Lin, L., Wang, Y., Zhang, Z., Zhang, F., He, J., 2018. Shifting plant species composition in response to climate change stabilizes grassland primary production. Proc. Natl. Acad. Sci. 115, 4051–4056.
Lyapustin, A., Wang, Y., Xiong, X., Meister, G., Platnick, S., Levy, R., Angal, A., 2014. Scientific impact of MODIS C5 calibration degradation and C6+ improvements. Atmos. Meas. Tech. 7, 4353–4365.
Ma, Z., Liu, H., Mi, Z., Zhang, Z., Wang, Y., Xu, W., He, J., 2017. Climate warming reduces the temporal stability of plant community biomass production. Nat. Commun. 8, 15378.
Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature 386, 698–702.
Nemani, R.R., Keeling, C.D., Hashimoto, H., Jolly, W.M., Piper, S.C., Tucker, C.J., ... Running, S.W., 2003. Climate-driven increases in global terrestrial net primary production from 1982 to 1999. Science 300, 1560–1563.
Niu, Y., Yang, S., Zhou, J., Chu, B., Ma, S., Zhu, H., Hua, L., 2019. Vegetation distribution along mountain environmental gradient predicts shifts in plant community response to climate change in alpine meadow on the Tibetan Plateau. Sci. Total Environ. 650, 505–514.
Ouyang, Z., Zheng, H., Xiao, Y., Polasky, S., Liu, J., Xu, W., Daily, G.C., 2016. Improvements in ecosystem services from investments in natural capital. Science 352, 1455–1459.
Palazzi, E., Filippi, L., von Hardenberg, J., 2017. Insights into elevation-dependent warming in the Tibetan Plateau-Himalayas from CMIP5 model simulations. Clim. Dynam. 48, 3991–4008.
Pepin, N., Bradley, R.S., Diaz, H.F., Baraer, M., Caceres, E.B., Forsythe, N., ... Yang, D.Q., 2015. Elevation-dependent warming in mountain regions of the world. Nat. Clim. Chang. 5, 424–430.
Peters, M.K., Hemp, A., Appelhans, T., Becker, J.N., Behler, C., Classen, A., Steffan-Dewenter, I., 2019. Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. Nature 568, 88–92.
Piao, S., Fang, J., He, J., 2006. Variations in vegetation net primary production in the Qinghai-Xizang Plateau, China, from 1982 to 1999. Clim. Chang. 74, 253–267.
Piao, S., Cui, M., Chen, A., Wang, X., Ciais, P., Liu, J., Tang, Y., 2011. Altitude and temperature dependence of change in the spring vegetation green-up date from 1982 to 2006 in the Qinghai-Xizang Plateau. Agric. For. Meteorol. 151, 1599–1608.
Prevéy, J., Vellend, M., Rüger, N., Hollister, R.D., Bjorkman, A.D., Myers-Smith, I.H., Rixen, C., 2017. Greater temperature sensitivity of plant phenology at colder sites: implications for convergence across northern latitudes. Glob. Chang. Biol. 23, 2660–2671.
Qiu, B., Li, W., Wang, X., Shang, L., Song, C., Guo, W., Zhang, Y., 2019. Satellite-observed solar-induced chlorophyll fluorescence reveals higher sensitivity of alpine ecosystems to snow cover on the Tibetan Plateau. Agric. For. Meteorol. 271, 126–134.
Ran, Y., Li, X., Cheng, G., 2018. Climate warming over the past half century has led to thermal degradation of permafrost on the Qinghai–Tibet Plateau. Cryosphere 12, 595–608.
Robertson, T.R., Bell, C.W., Zak, J.C., Tissue, D.T., 2009. Precipitation timing and magnitude differentially affect aboveground annual net primary productivity in three perennial species in a Chihuahuan Desert grassland. New Phytol. 181, 230–242.
Rudgers, J.A., Chung, Y.A., Maurer, G.E., Moore, D.I., Muldavin, E.H., Litvak, M.E., Collins, S.L., 2018. Climate sensitivity functions and net primary production: a framework for incorporating climate mean and variability. Ecology 99, 576–582.
Scurlock, J., Hall, D.O., 1998. The global carbon sink: a grassland perspective. Glob. Chang. Biol. 4, 229–233.
Seddon, A.W.R., Macias-Fauria, M., Long, P.R., Benz, D., Willis, K.J., 2016. Sensitivity of global terrestrial ecosystems to climate variability. Nature 531, 229–232.
Sheffield, J., Goteti, G., Wood, E.F., 2006. Development of a 50-year high-resolution global dataset of meteorological forcings for land surface modeling. J. Clim. 19, 3088–3111.
Shen, M., Zhang, G., Cong, N., Wang, S., Kong, W., Piao, S., 2014. Increasing altitudinal gradient of spring vegetation phenology during the last decade on the Qinghai–Tibetan Plateau. Agric. For. Meteorol. 189-190, 71–80.
Shen, M., Piao, S., Cong, N., Zhang, G., Jassens, I.A., 2015a. Precipitation impacts on vegetation spring phenology on the Tibetan Plateau. Glob. Chang. Biol. 21, 3647–3656.
Shen, M., Piao, S., Jeong, S., Zhou, L., Zeng, Z., Ciais, P., Yao, T., 2015b. Evaporative cooling over the Tibetan Plateau induced by vegetation growth. Proc. Natl. Acad. Sci. 112, 9299–9304.
Shen, M., Piao, S., Chen, X., An, S., Fu, Y.H., Wang, S., Janssens, I.A., 2016a. Strong impacts of daily minimum temperature on the green-up date and summer greenness of the Tibetan Plateau. Glob. Chang. Biol. 22, 3057–3066.
Shen, M., Piao, S., Dorji, T., Liu, Q., Cong, N., Chen, X., Zhang, G., 2016b. Plant phenological responses to climate change on the Tibetan Plateau: research status and challenges. National Science Review 2, 454–467.
Sun, H., Zheng, D., Tandong, Y., Zhang, Y., 2012. Protection and construction of the national ecological security shelter zone on Tibetan Plateau. Acta Geograph. Sin. 1, 3–12.
Suonan, J., Classen, A.T., Sanders, N.J., He, J.S., 2019. Plant phenological sensitivity to climate change on the Tibetan Plateau and relative to other areas of the world. Ecosphere 10, e02543.
Tang, W.J., Yang, K., Qin, J., Cheng, C.C.K., He, J., 2011. Solar radiation trend across China in recent decades: a revisit with quality-controlled data. Atmos. Chem. Phys. 11, 393–406.
Tao, J., Zhang, Y., Dong, J., Fu, Y., Zhu, J., Zhang, G., Xi, Y., 2015. Elevation-dependent relationships between climate change and grassland vegetation variation across the Qinghai-Xizang Plateau. Int. J. Climatol. 35, 1638–1647.
Tao, J., Xu, T., Dong, J., Yu, X., Jiang, Y., Zhang, Y., Wang, S., 2018. Elevation-dependent effects of climate change on vegetation greenness in the high mountains of southwest China during 1982–2013. Int. J. Climatol. 38, 2029–2038.
Wang, C.T., Long, R.J., Wang, Q.J., Ding, L.M., Wang, M.P., 2007. Effects of altitude on plant-species diversity and productivity in an alpine meadow, Qinghai–Tibetan plateau. Aust. J. Bot. 55, 110.
Wang, S., Wang, C., Duan, J., Zhu, X., Xu, G., Luo, C., ... Du, M., 2014. Timing and duration of phenological sequences of alpine plants along an elevation gradient on the Tibetan plateau. Agric. For. Meteorol. 189–190, 220–228.
Willis, K.J., Jeffers, E.S., Tovar, C., 2018. What makes a terrestrial ecosystem resilient? Science 359, 988–989.
Xu, X., Chen, H., Levy, J.K., 2008. Spatiotemporal vegetation cover variations in the Qinghai-Tibet Plateau under global climate change. Science Bulletin 53, 915–922.

Yang, Y., Hopping, K.A., Wang, G., Chen, J., Peng, A., Klein, J.A., 2018. Permafrost and drought regulate vulnerability of Tibetan Plateau grasslands to warming. Ecosphere 9, e02233.

Yao, T., Xue, Y., Chen, D., Chen, F., Thompson, L., Cui, P., ... Department O. E. S, 2019. Recent Third Pole's rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multi-disciplinary approach with observation, modeling and analysis. B. Am. Meteorol. Soc. https://doi.org/10.1175/BAMS-D-17-0057.1.

You, Q., Fraedrich, K., Ren, G., Pepin, N., Kang, S., 2013. Variability of temperature in the Tibetan Plateau based on homogenized surface stations and reanalysis data. Int. J. Climatol. 33, 1337–1347.

You, N., Meng, J., Zhu, L., 2018. Sensitivity and resilience of ecosystems to climate variability in the semi-arid to hyper-arid areas of Northern China: a case study in the Heihe River Basin. Ecol. Res. 33, 161–174.

Zeng, Z., Piao, S., Li, L.Z.X., Zhou, L., Ciais, P., Wang, T., Wang, Y., 2017. Climate mitigation from vegetation biophysical feedbacks during the past three decades. Nat. Clim. Chang. 7, 432–436.

Zhang X. S., Sun S., Yong S., Al E., 2007. Vegetation map of the People's Republic of China (1:1000000).

Zhang, Y., Qi, W., Zhou, C., Ding, M., Liu, L., Gao, J., Zheng, D., 2014. Spatial and temporal variability in the net primary production of alpine grassland on the Tibetan Plateau since 1982. J. Geogr. Sci. 24, 269–287.

Zhao, D., Wu, S., 2016. Spatial and temporal variability of key bio-temperature indicators on the Qinghai-Tibetan Plateau for the period 1961–2013. Int. J. Climatol. 36, 2083–2092.

Zheng, D., 1996. The system of physico-geographical regions of the Qinghai-Xizang (Tibet) plateau. Sci. China Earth Sci 39, 410–417.

Zhong, L., Ma, Y., Salama, M.S., Su, Z., 2010. Assessment of vegetation dynamics and their response to variations in precipitation and temperature in the Tibetan Plateau. Clim. Chang. 103, 519–535.

Zu, J., Zhang, Y., Huang, K., Liu, Y., Chen, N., Cong, N., 2018. Biological and climate factors co-regulated spatial-temporal dynamics of vegetation autumn phenology on the Tibetan Plateau. Int. J. Appl. Earth Obs. 69, 198–205.